An Implementation of Hybrid CFD/BEM Technology For Prediction Acoustic Environments Using Open-Source Software

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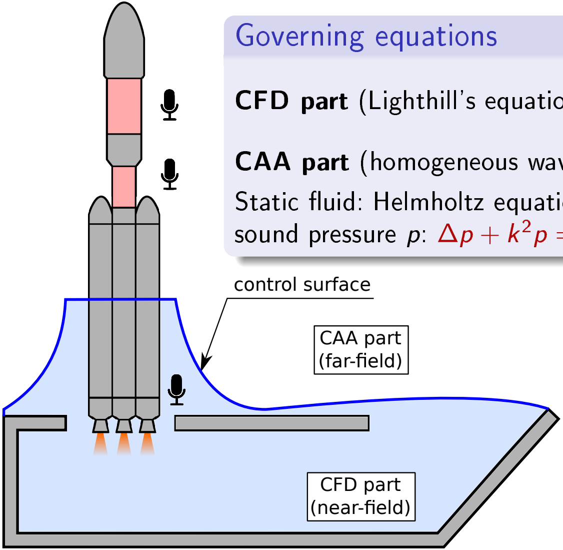
Introduction

Sound source	SPL, dB
Diesel truck, 10 m away	90
Chainsaw, 1 m distance	110
Threshold of discomfort, near an ear	120
Threshold of pain, near an ear	130-140
Jet engine, 1 m distance	130-160

Danger zone: $>$140 dB!

Hybrid CFD/BEM modelling



Governing equations

CFD part (Lighthill's equation [7]): $\frac{\partial^2 \rho}{\partial t^2} - c^2 \Delta \rho \neq 0$;

CAA part (homogeneous wave equation): $\frac{\partial^2 \rho}{\partial t^2} - c^2 \Delta \rho = 0$.

Static fluid: Helmholtz equation for complex amplitude of sound pressure p: $\Delta p + k^2 p = 0$.

Estimates of resources

Pure CFD modelling (near-field + far-field): ≈530 billions cells.

Hybrid modelling: ≈10 millions cells in near-field, ≈30 000 on the control surface.

Boundary conditions

CFD part

Various boundary conditions which satisfied to mathematical model of fluid flows.

BEM part

Control surface: interpolate pressure data from gas dynamic solution.
Use Dirichlet boundary conditions:

$$p(\mathbf{x}_c) = p^*(\mathbf{x}_c).$$

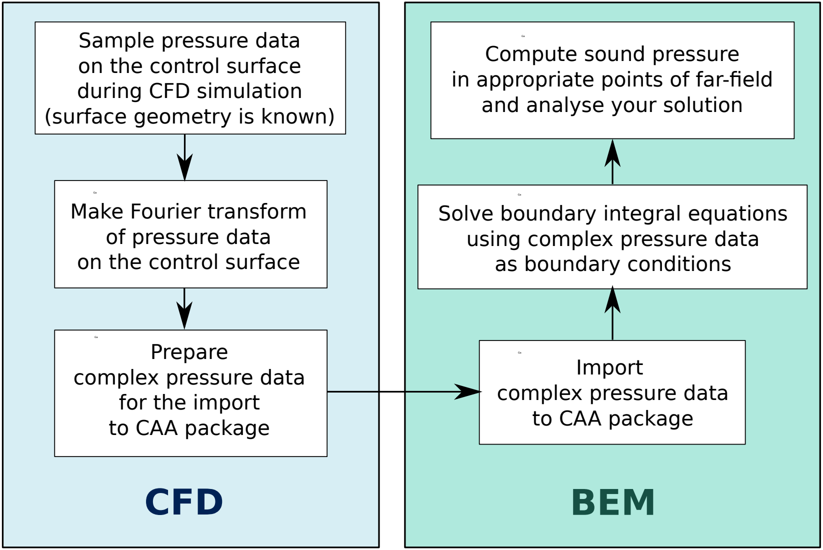
Reflecting surfaces: use Neumann boundary conditions for sound reflection:

$$\frac{\partial p(\mathbf{x}_c)}{\partial \mathbf{n}} = 0.$$

"Infinity": no surface, solution automatically satisfies to Sommerfeld boundary conditions [3]:

$$\left| \frac{\mathbf{x}}{|\mathbf{x}|} \cdot \nabla p(\mathbf{x}) - ikp(\mathbf{x}) \right| = O\left(\frac{1}{|\mathbf{x}|^2}\right) \text{ as } |\mathbf{x}| \to \infty.$$

General scheme of the technology implementation



Sample pressure data
on the control surface
during CFD simulation
(surface geometry is known)

Make Fourier transform
of pressure data
on the control surface

Prepare
complex pressure data
for the import
to CAA package

CFD

Import
complex pressure data
to CAA package

Solve boundary integral equations
using complex pressure data
as boundary conditions

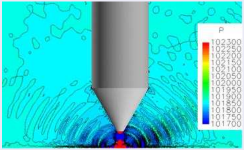
Compute sound pressure
in appropriate points of far-field
and analyse your solution

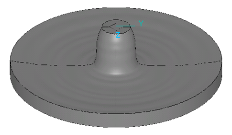
BEM

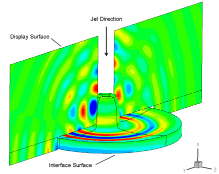
CFD/BEM technology implementation

Existing implementation (NASA) [6]

Example: Jet impingement noise from SHJAR (Small Hot Jet Aeroacoustics Rig)







Packages: Loci/CHEM for CFD part, FastBEM for CAA part (*commercial packages*).

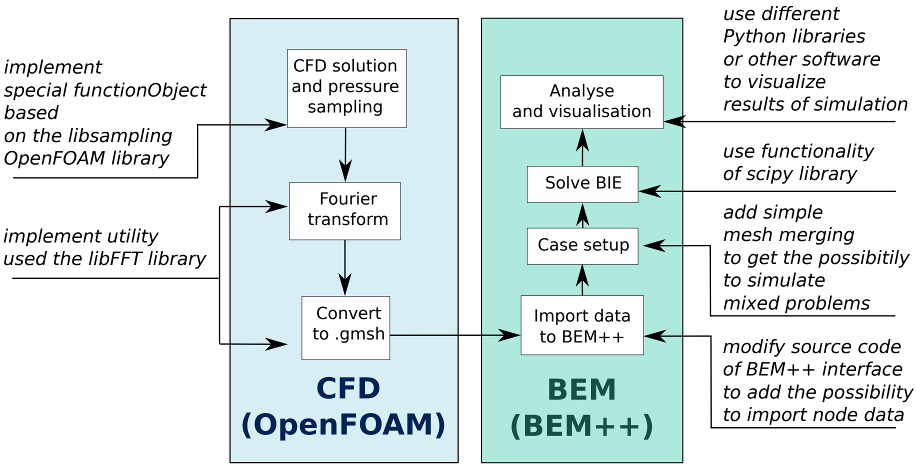
The main goal

To implement a hybrid model *using open-source packages*.

Chosen open-source packages

	Structure	Case description	Solver
OpenFOAM	C++ apps and dynamic libraries, set of overloaded primitive objects and functions.	Folder which contains a set of dictionaries with description of different parts of case.	Gas dynamic solver (rhoPimpleFoam, rhoCentralFoam, pisoCentralFoam...)
BEM++	C++ kernel and Python interface.	One file with Python script for one case. Standard Python libraries can be used.	No separate solvers. Use implemented elliptic operators to construct needed scheme in the file for specific case.

Scheme of technology implementation using OpenFOAM and BEM++



implement special functionObject based on the libsampling OpenFOAM library

implement utility used the libFFT library

CFD solution and pressure sampling

Fourier transform

Convert to .gmsh

CFD (OpenFOAM)

Import data to BEM++

Case setup

Solve BIE

Analyse and visualisation

BEM (BEM++)

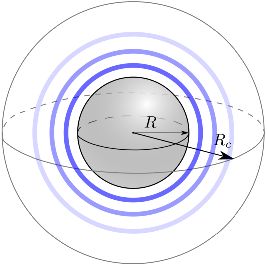
use different Python libraries or other software to visualize results of simulation

use functionality of scipy library

add simple mesh merging to get the possibilitiy to simulate mixed problems

modify source code of BEM++ interface to add the possibility to import node data

Pulsating sphere



CFD parameters

Size of flow domain: $10 \times 10 \times 10$ m.
Solver: `pisoCentralFoam`.
Mesh cell size: $\approx$ 20 cells per wave length.

BEM parameters

Radius of control surface: $R_c = 2$ m.
Size of mesh cells: $\approx$ 5, 10, 20 cpwl.
Combined [3] formulation of BIE.

Input data

Radius of sphere: $R = 1$ m
Pressure oscillations: $p(R,t) = A\sin(2\pi f t)$
Pressure amplitude: $A = 1$ Pa
Frequency: $f = 100$ Hz
Speed of sound: $c = 343$ m/s
Density of air: $\rho_0 = 1204$ kg/m^3

Analytical solution

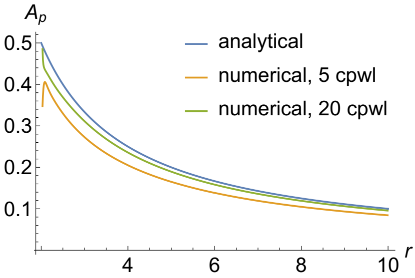
$$p(r,t) = \mathrm{Re}\left[\frac{A}{r}e^{-i(\omega t - kr)}\right];$$

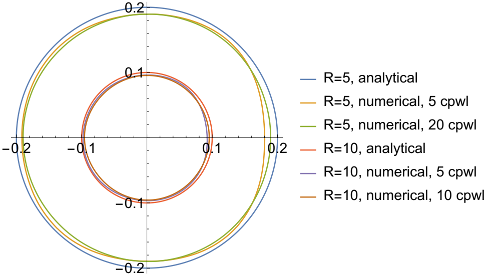
here $\omega = 2\pi f$, $A = \rho_0 c U_0 e^{-ikR}$, $k = \omega / c$.

Simulation time

CFD part: 0.2 s (20 periods)
BEM part: 0.06 s

Pulsating sphere

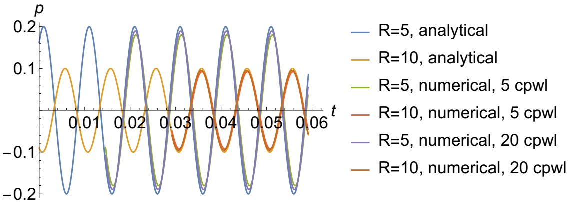




Execution time

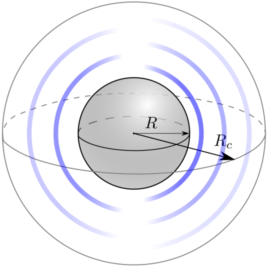
CFD (36 kernels): ≈ 1.5 h.
BEM (4 kernels):

- 5 cpwl: 3 s;
- 10 cpwl: 70 s;
- 20 cpwl: 140 s.



Relative error: ≈ 7%

Vibrating sphere



CFD parameters

Size of flow domain:
10 × 10 × 10 m.
Solver:
`pisoCentralFoam`.
Mesh cell size:
≈ 20 cells per wave length.

BEM parameters

Radius of control surface: $R_c = 2$ m.
Size of mesh cells:
≈ 5, 10, 20 cpwl.
Combined [3] formulation of BIE.

Input data

Radius of sphere: $R = 1$ m
Velocity oscillations:
$U(R, \theta, t) = A \sin(2\pi f t) \cos\theta$
Velocity amplitude: $A = 1$ m/s
Frequency: $f = 100$ Hz
Speed of sound: $c = 343$ m/s
Density of air: $\rho_0 = 1204$ kg/m^3

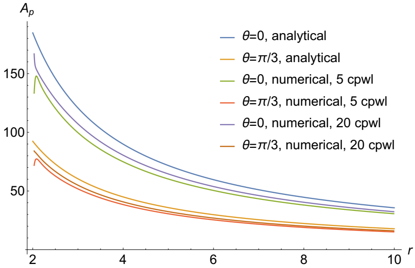
Analytical solution

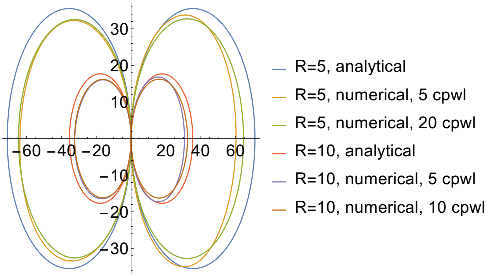
$$p(r, \theta, t) =$$

$$= \mathrm{Re}\left[\left(1 + \frac{1}{ikr}\right) \frac{-A_1 e^{-i(\omega t - kr)}}{kr} \cos\theta\right],$$

where $A_1 = -\dfrac{\rho_0 c k a U_0 e^{ika}}{1 - \frac{2}{(ka)^2} + \frac{2}{ika}}$.

Vibrating sphere





Execution time

CFD (36 kernels): ≈ 1.5 h.
BEM (4 kernels):

- 5 cpwl: 3 s;
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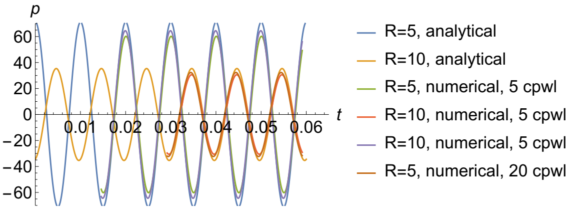
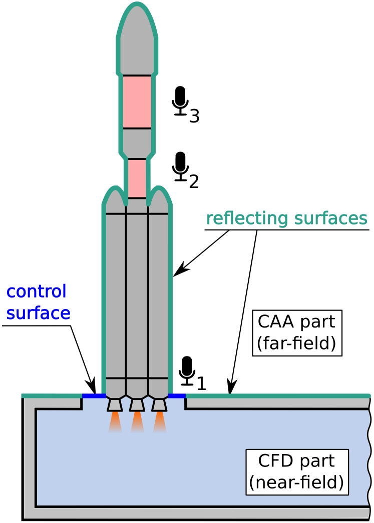


Relative error: ≈ 7%

Launch vehicle lift-off

First results



CFD parameters

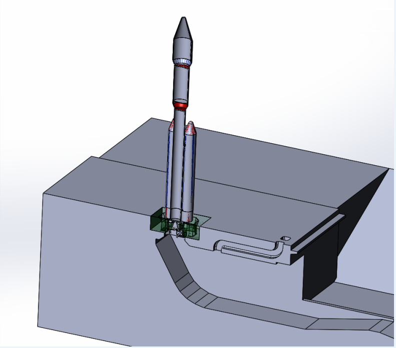
Number of cells: $\approx$ 7 mln.
Solver: `pisoCentralFoam`.
Simulation time: 0.1 s.

BEM parameters

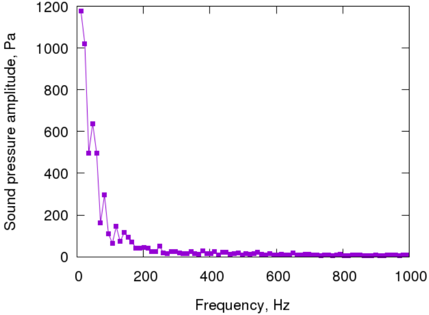
Control surface: 343 nodes, 516 triangle cells.
Reflecting surfaces: 32391 nodes, 63630 triangle elements.
Combined [3] formulation of BIE for mixed exterior problem (to avoid non-uniqueness of solution).

Launch vehicle lift-off: CFD part

CFD geometry



Sound pressure spectrum on the control surface



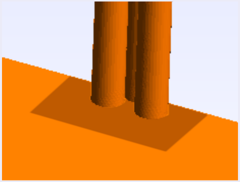
Execution time: ≈ 15 h (144 kernels)

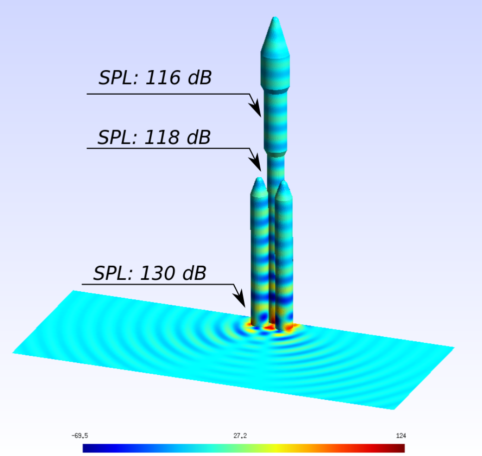
Launch vehicle lift-off: BEM part

Frequency: ≈ **100 Hz**.

Execution time: ≈ 1 hour (4 kernels).
Number of iterations for SLAE solution: ≈ 20 000.
Used solver: GMRES (SciPy implementation).

Control surface position





Conclusions

- Main stages of hybrid technology of far-field noise prediction were described.
- The first version of the hybrid technology implementation was designed using open-source software OpenFOAM and BEM++.
- Validation cases (pulsating sphere and oscillating sphere) were considered. Agreement with analytical solution is observed.
- Some factors has a large influence to the solution:
  - size of CFD mesh cells near the control surface;
  - size of triangle elements in the boundary mesh on the control surface;
  - interpolation scheme using for sampling;
  - number of frames used in complex pressure data calculation;
  - settings of numerical methods using both in CFD ans BEM parts.
- Possibility to use CFD/BEM technology in "large" cases has been presented.

Thank you for attention!

Literature I

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[3] S. Engleder, O. Steinbach. Modified boundary integral formulations for the Helmholtz equation // Journal of Mathematical Analysis and Applications. 2007. Vol. 331. Pp. 396–407.

[4] A. Kleefeld. The exterior problem for the Helmholtz equation with mixed boundary conditions in three dimensions // International Journal of Computer Mathematics. 2012. Vol. 89, No. 17. Pp. 2392–2409.

[5] BEM++. Documentation. URL: http://www.bempp.org/docs.html

Literature II

[6] A. Tosh, P. Liever, F. Owens. A High-Fidelity CFD/BEM Methodology For Launch Pad Acoustic Environment Prediction // 18th AIAA/CEAS Aeroacoustics Conference (33rd AIAA Aeroacoustics Conference), 04–06 June, 2012.

[7] M. E. Goldstein. Aeroacoustics. McGraw-Hill International Book Company. 1976. 293 p.